Current Progress on Design Work of High Power EUV-FEL based on ERL

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2015 Source Workshop

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The design study has been done under collaboration with a Japanese company.

Introduction

- >10kW class EUV sources are required for lithography

- Using technologies and knowledges we obtained through development of Compact ERL (cERL) and STF (Superconducting Test Facility) in KEK, we have designed EUV-FEL light source based on ERL.

- Target of prototype of EUV-FEL

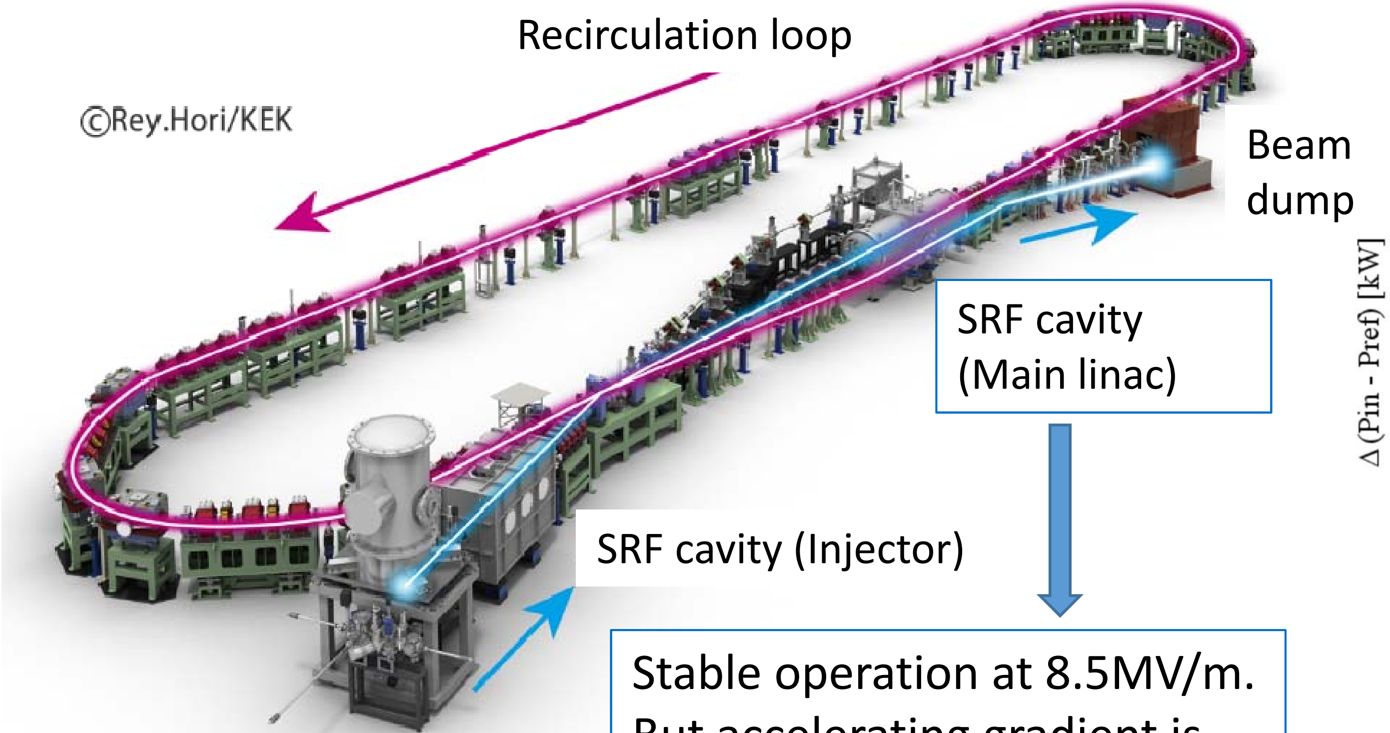
  10kW power @ 13.5 nm, 800MeV & 10mA beam

  Energy recovery of 800MeV x 10mA = 8MW

- Use available technology without too much development

Operation of cERL

Start beam operation from 2014/Jan. Energy recovery successful. 20MeV, 100uA at present



SRF cavity (Main linac)

500kV Electron gun

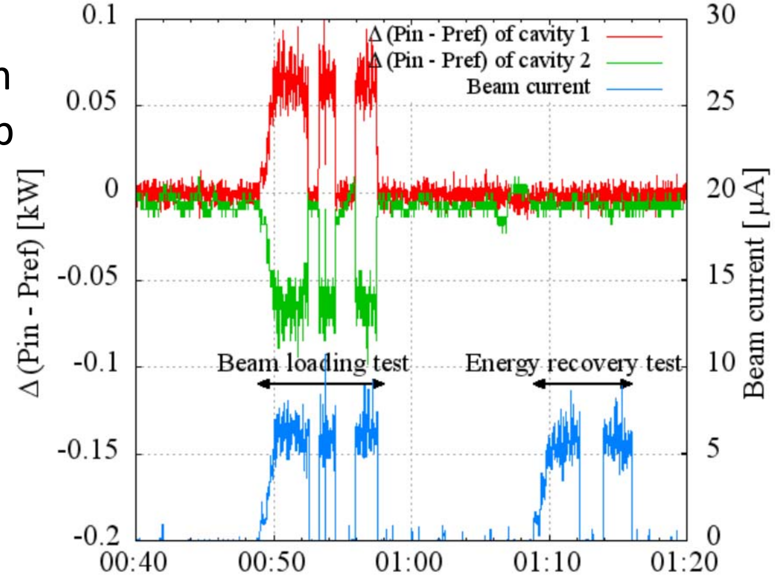
Very stable operation at 390kV. Plan to upgrade to 500kV.
At present 100uA operation. Upgrade to 1mA and then 10mA near future.

Stable operation at 8.5MV/m. But accelerating gradient is limited by field emission.

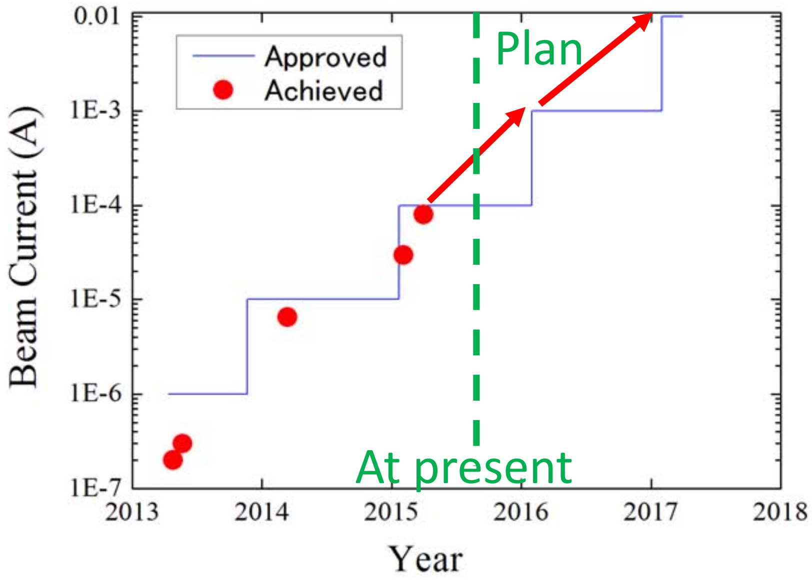
Energy recovery of
E_beam(MeV)xI_beam(mA)

Given power to
beam acceleration
= Obtained power from
beam decceleration

Successful energy recovery

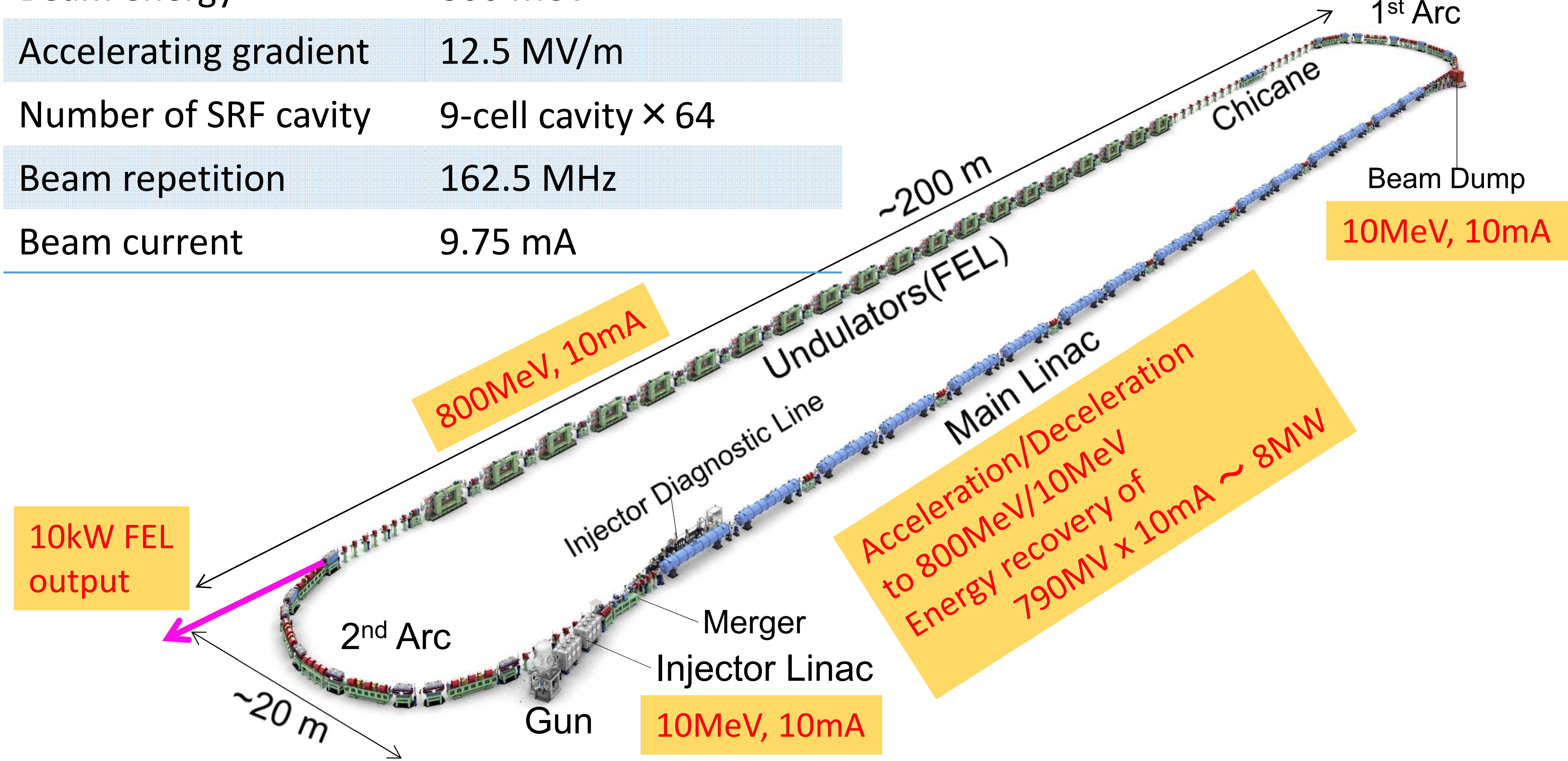


Upgrade of beam current
(S. Sakanaka, IPAC15, TUBC1)



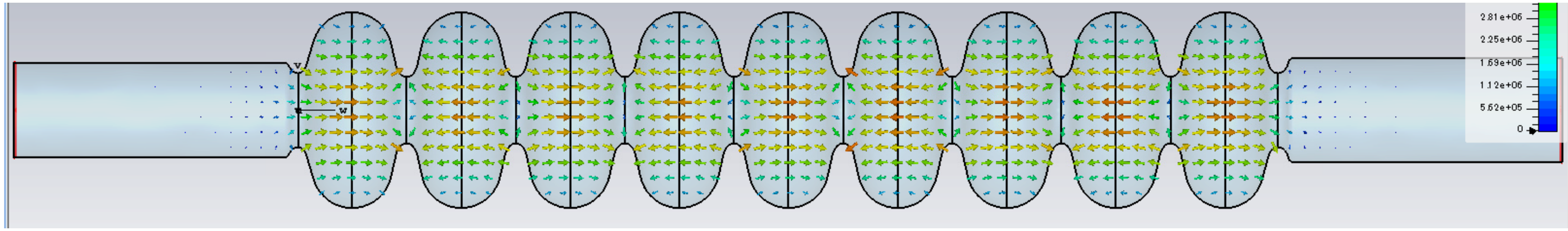
EUV-FEL Design

Parameter	Specification
Wavelength	13.5 nm
Output power	10 kW
Bunch chare	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 MHz
Beam current	9.75 mA

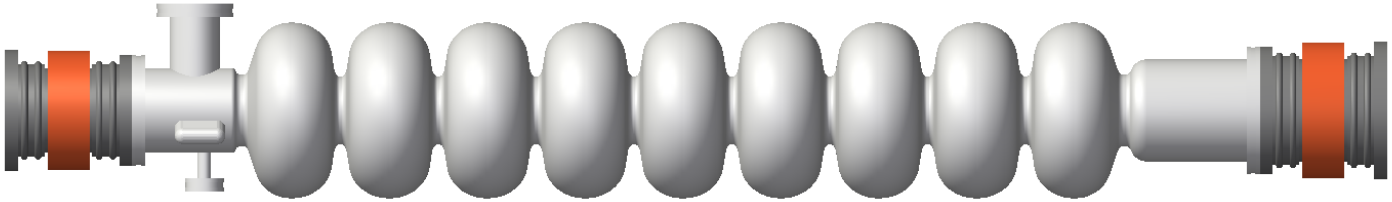


Design of Main Linac Cavity

EUV cavity – TESLA-type 9-cell cavity + Laege beam pipes(100ϕ & 110ϕ)



cERL cavity (Model 2) – HOM damped cavity for 100mA operation

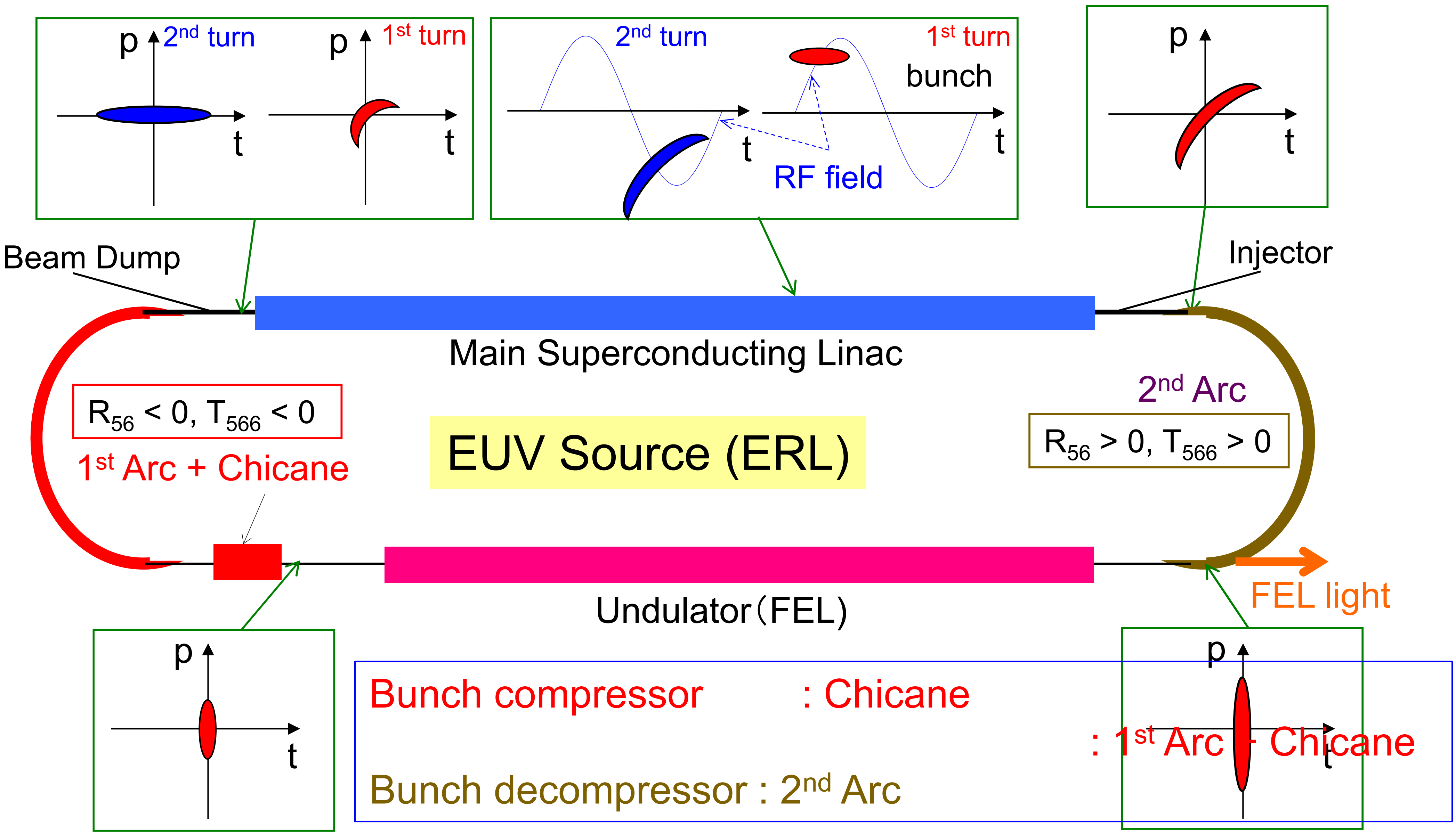


Parameters for acceleration mode

	ERL Model 2	EUV		ERL Model 2	EUV
Frequency	1300 MHz	**1300 MHz**	Iris diameter	80 mm	70 mm
R_{sh}/Q	897 Ω	**~1000 Ω**	$Q_o \times R_s$	289 Ω	~270 Ω
E_p/E_{acc}	3.0	**~ 2.0**	H_p/E_{acc}	42.5 Oe/(MV/m)	~42.0 Oe/(MV/m)

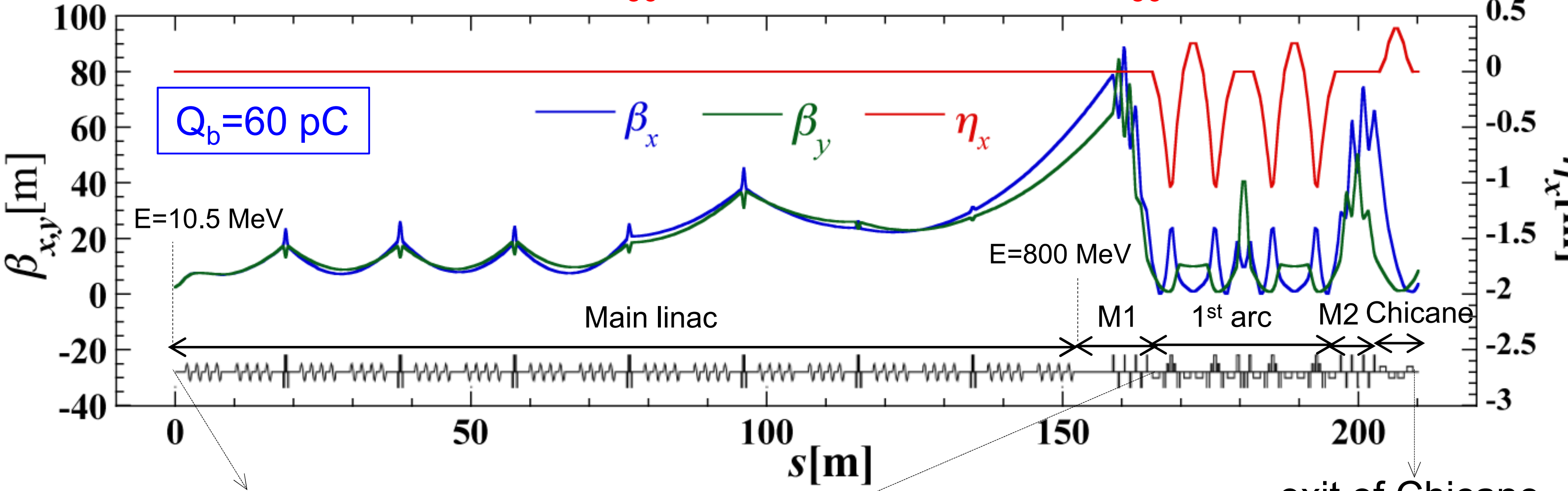
Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.

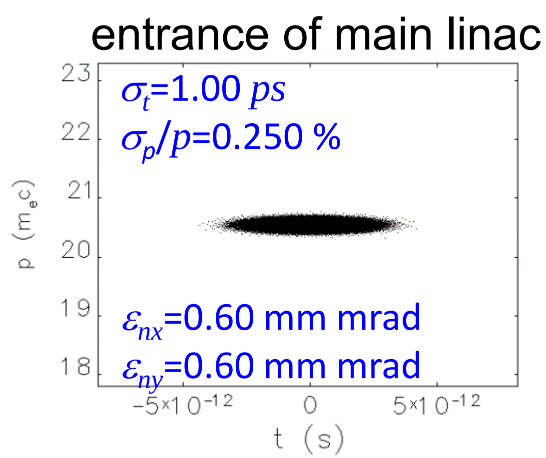
Bunch compression and decompression scheme

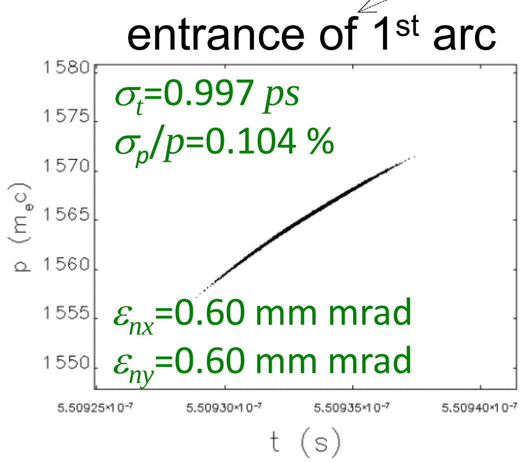


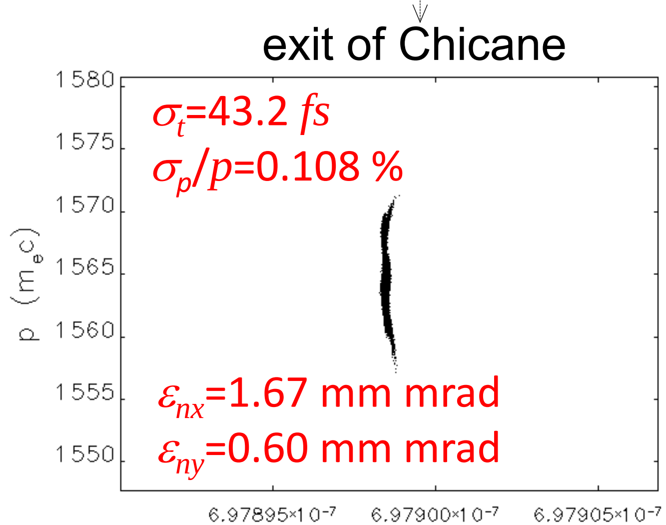
Bunch Compression by Arc & Chicane

Main Linac + 1st Arc（R_{56}=-0.15 m）+ Chicane (R_{56}=-0.15 m)









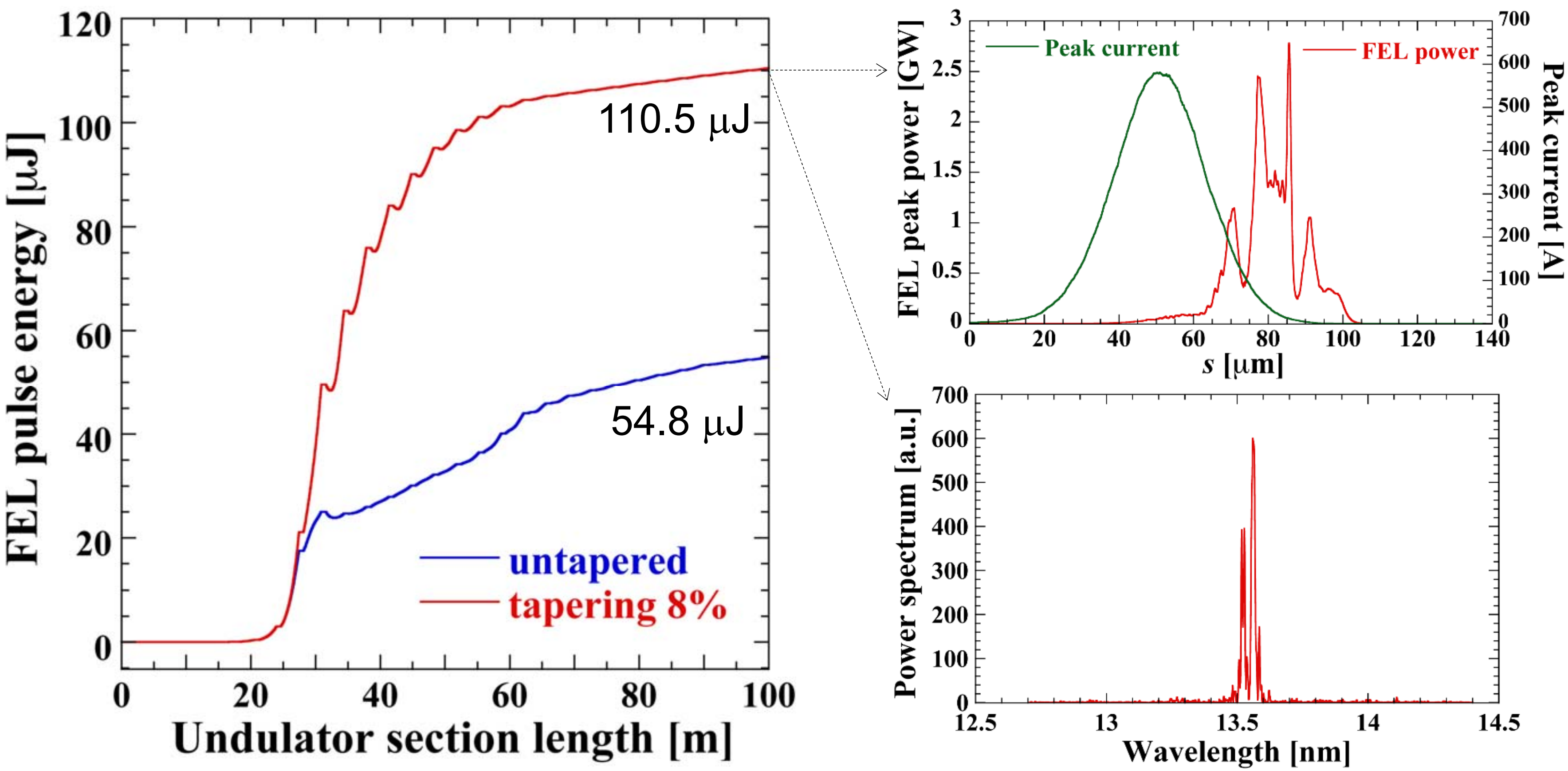
t (s)

RF phase and sextupole strengths maximizing the Pierce parameter

K_2 (SX1)=-110.5 [m^{-3}], K_2 (SX4) =41.4 [m^{-3}], ϕ_{RF}=82.4 [deg]

FEL Simulation

Electron beam parameters: E=800 MeV, Q_b=60 pC, f_b=162.5/325 MHz
Helical undulator parameters: K=1.652, λ_u=28 mm, L_u=2.8m (segment length)
Bunch compression scheme: 1^{st} Arc + Chicane



FEL power without tapering: 8.9/17.8 kW @ 9.75/19.5 mA
FEL power with 8% tapering: 18.0/36.0 kW @ 9.75/19.5 mA

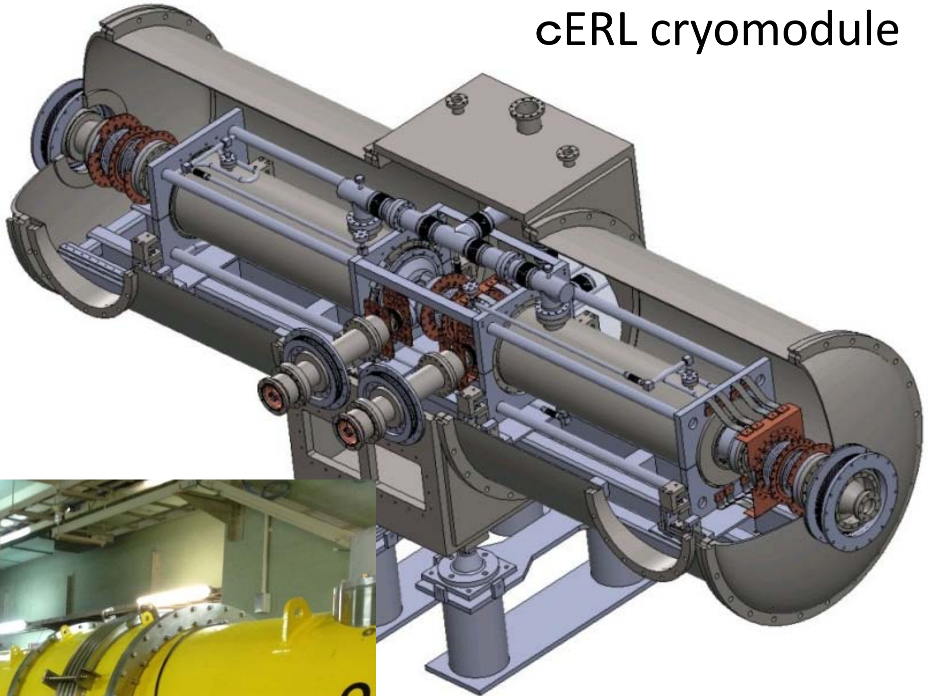
Requirement for SRF cryomodule

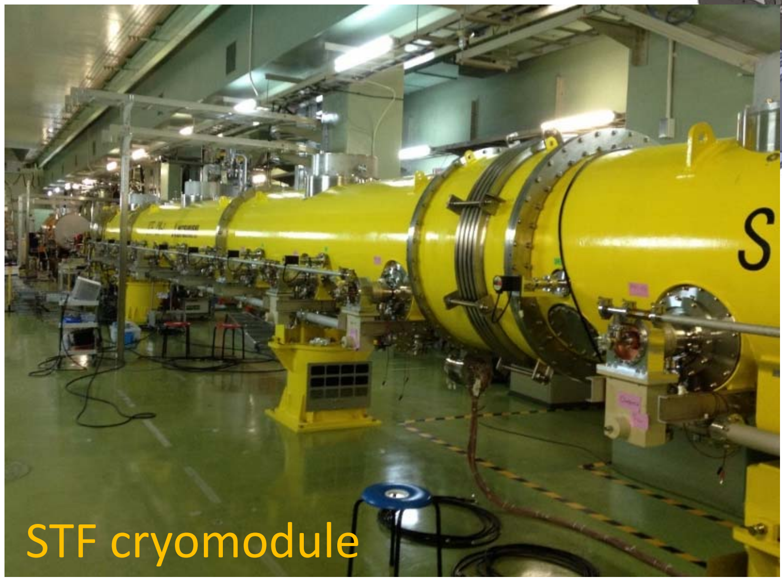
- Accelerating gradient(Eacc) ～12.5MV/m
  - Suppress field emission. → low surface field (low Epeak)
  - Qo > 1 x 10^{10}, high Q (=low loss) is desirable
- Beam current ～10mA (x2 for energy recovery)
  - Suppress BBU (Beam breakup) instability
  - Handling monopole HOM heat load(10～30W)
- Cryogenic loss
  - Cavity loss: $P = V^2/Rsh$
  - Low Eacc → low cryogenic loss
  - ～15W/cavity -> 15W x 64 = (Total) 1kW (@2K)
- RF (amplitude and phase) stability
  - Achieve 0.02% rms and 0.02 deg rms for amplitude and phase at cERL. Are they enough for EUV-FEL?(under discussion)
- Alignment
  - Around 1mm precision. Is it acceptable for EUV-FEL?
- Operation stability
  - More stable is better. Stability is big target of design.
  - Lower Eacc is one choice for more stable and less cryogenic loss.

Concept of main linac cryomodule

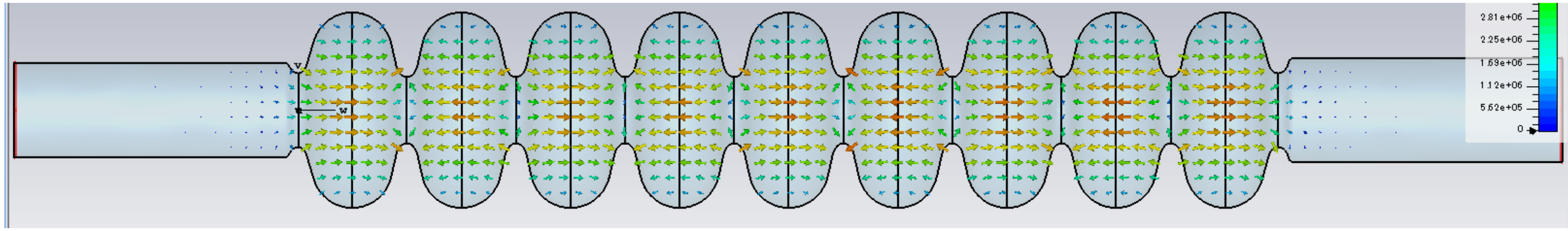
- We have been designed prototype cryomodule.
- Based on STF cryomodule (developed for Linear Collider), which is pulse operation
- Modified for CW operation, merge some cERL components
- Optimized for EUV cryomodule.
- Most reliable design.
- One module includes 4 cavities.
  - Q-magnet: Each 8 cavities
  - Steering and BPM: Each 4 cavities(?)

cERL cryomodule





Cavity / HOM damping



- Final cavity design is under optimization
  - ➢ Center cell is TESLA shape, with Epeak/Eacc ～ 2.0
  - ➢ Both end cells are optimized with large beam tubes (100ϕ & 110ϕ)
  - ➢ BBU threshold should be around 200 mA

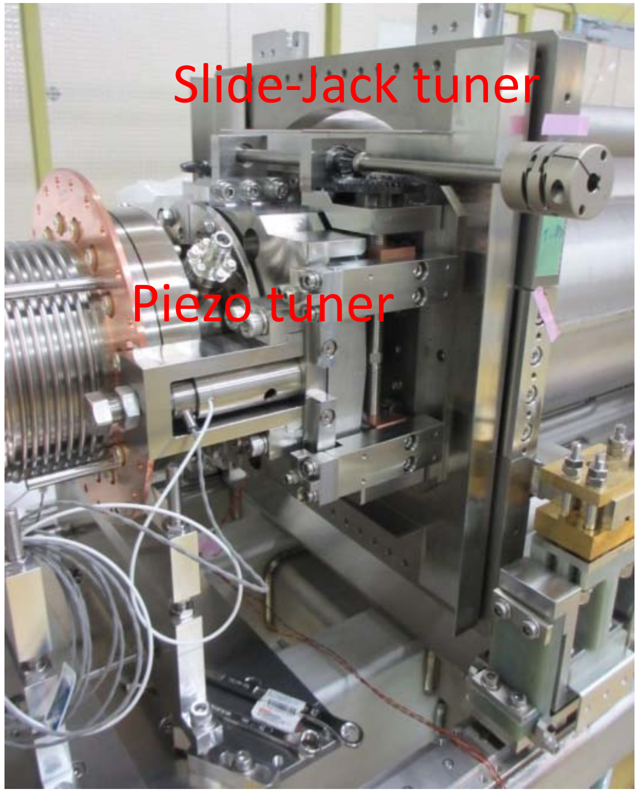
- Combination use of HOM absorber / HOM coupler(antenna type)
  - ➢ cERL HOM absorber(ferrite) has cracks → not good for SRF usage
  - ➢ We try to fabricate new absorber using AlN. (This is challenge!)
  - ➢ Start from compact / small AlN absorber, but with help from antenna type HOM coupler.
  - ➢ High power test of RF cable /connector in vacuum shows promising results.

Input coupler

- Pulse version was designed for STF and modified for CW at cERL
- Qext = 2 x 10^7 require 4～5kW input power for Eacc = 12.5 MV/m
- cERL coupler working well (very similar specification with EUV-FEL)
- Apply for EUV-FEL with some trial of compact version.

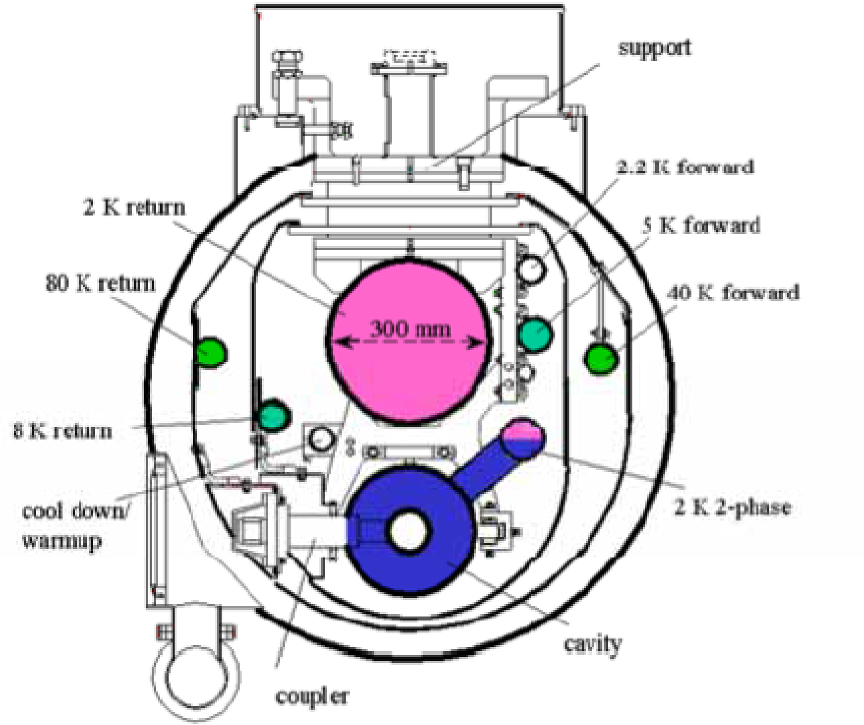
Frequency tuner

- Rough tuning by Slide-Jack tuner, controlled by motor
  - Full stroke 3mm (～1MHz)
- Fine tuning by piezo tuner
  - Precision < nm
- Working very well at cERL and STF
- Apply for EUV-FEL



Cryomodule (1) –STF / TESLA type

- Follow STF/TESLA cryomodule with some modification.
- Cavity is hung from 2K He return pipe, witch is also hung from top of cryomodule.
- Magnetic shield is inside He jacket.
- He level at middle of 2K 2-phase pipe.
- There are 5K and 80K thermal shields.

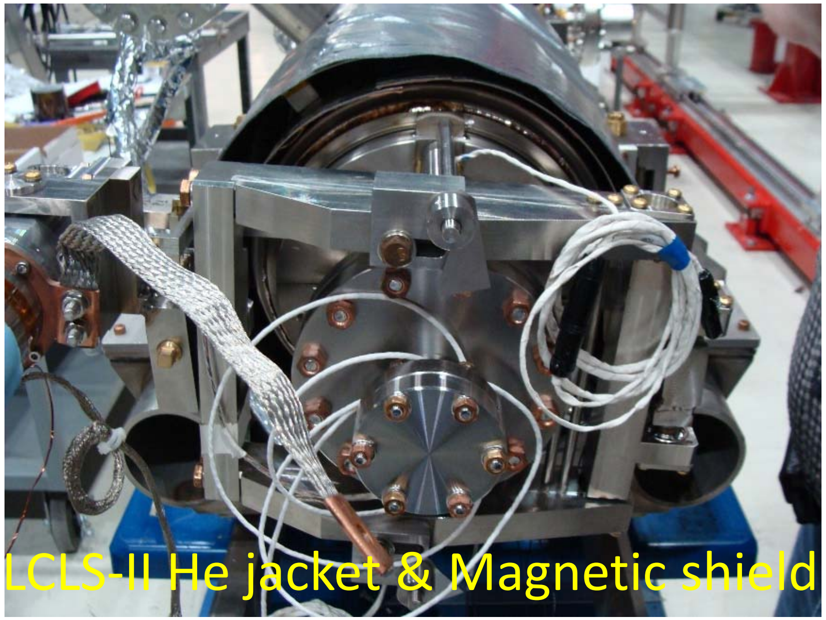


DESY-TESLA-TYPE-III
Cryomodule cross section
From OHO06 slide of Ohuchi-san

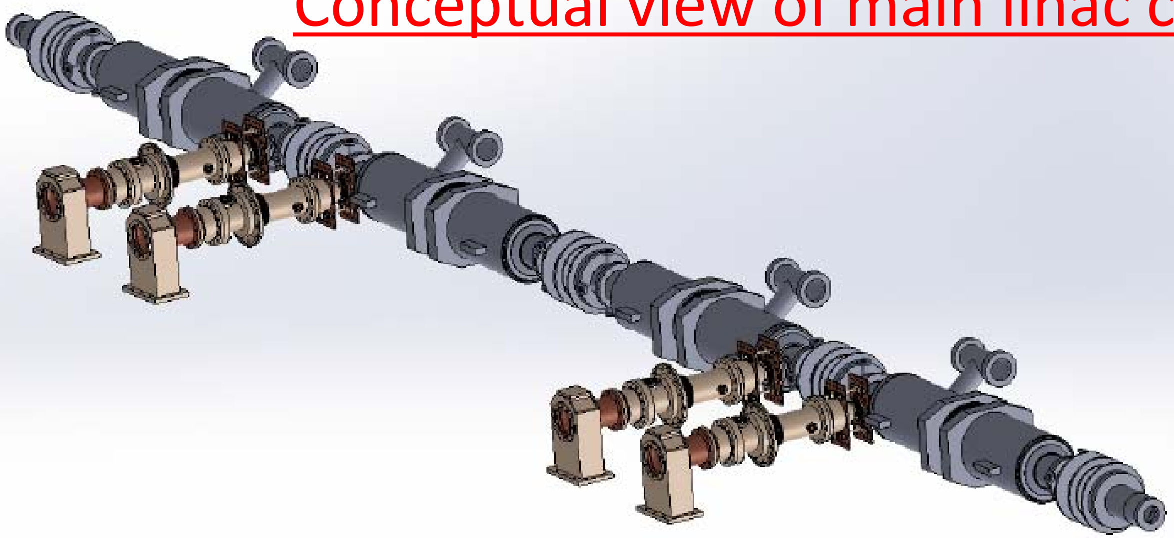
Cryomodule (2) ～Modification/discussion

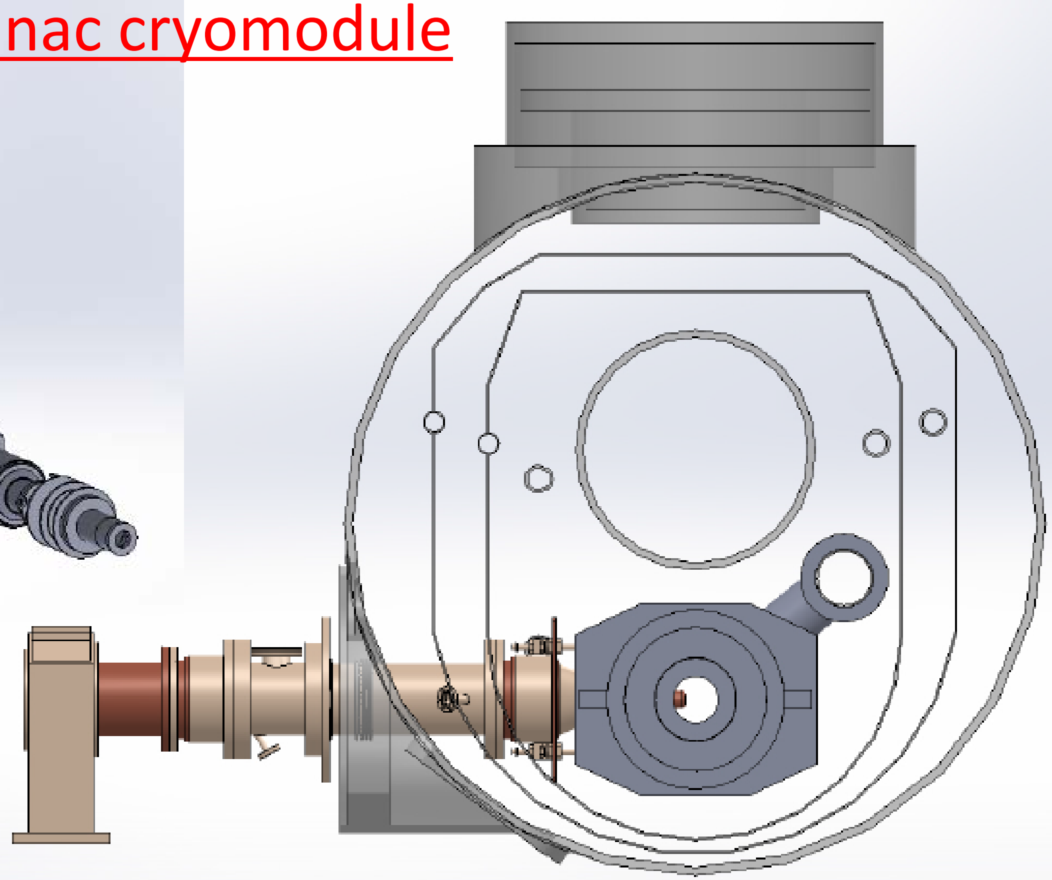
- Chimney from He jacket to 2-phase pipe
  - Chimney limits thermal conductivity at CW operation
  - Larger diameter is essential
- 2K He return pipe
  - Diameter of 300ϕ is optimized for ILC. Should optimize for EUV as support structure
- Design for high-Q
  - Enhanced magnetic shielding
  - Cooling procedure etc.
- Gate valve
  - Want to put “clean” gate valve inside cryomodule (vacuum).
  - Cooling if needed.
- Alignment
  - Applied laser based alignment monitor, which is used for cERL.

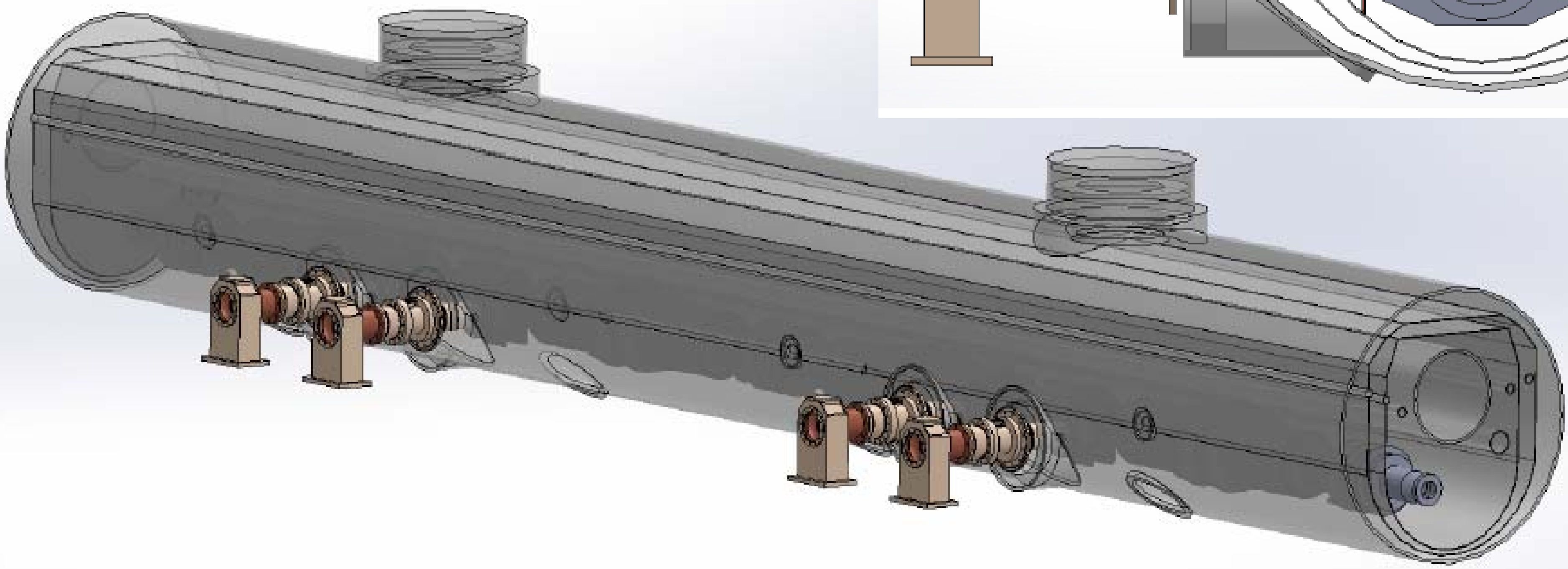

LCLS-II He jacket & chimney


LCLS-II He jacket & Magnetic shield

Conceptual view of main linac cryomodule

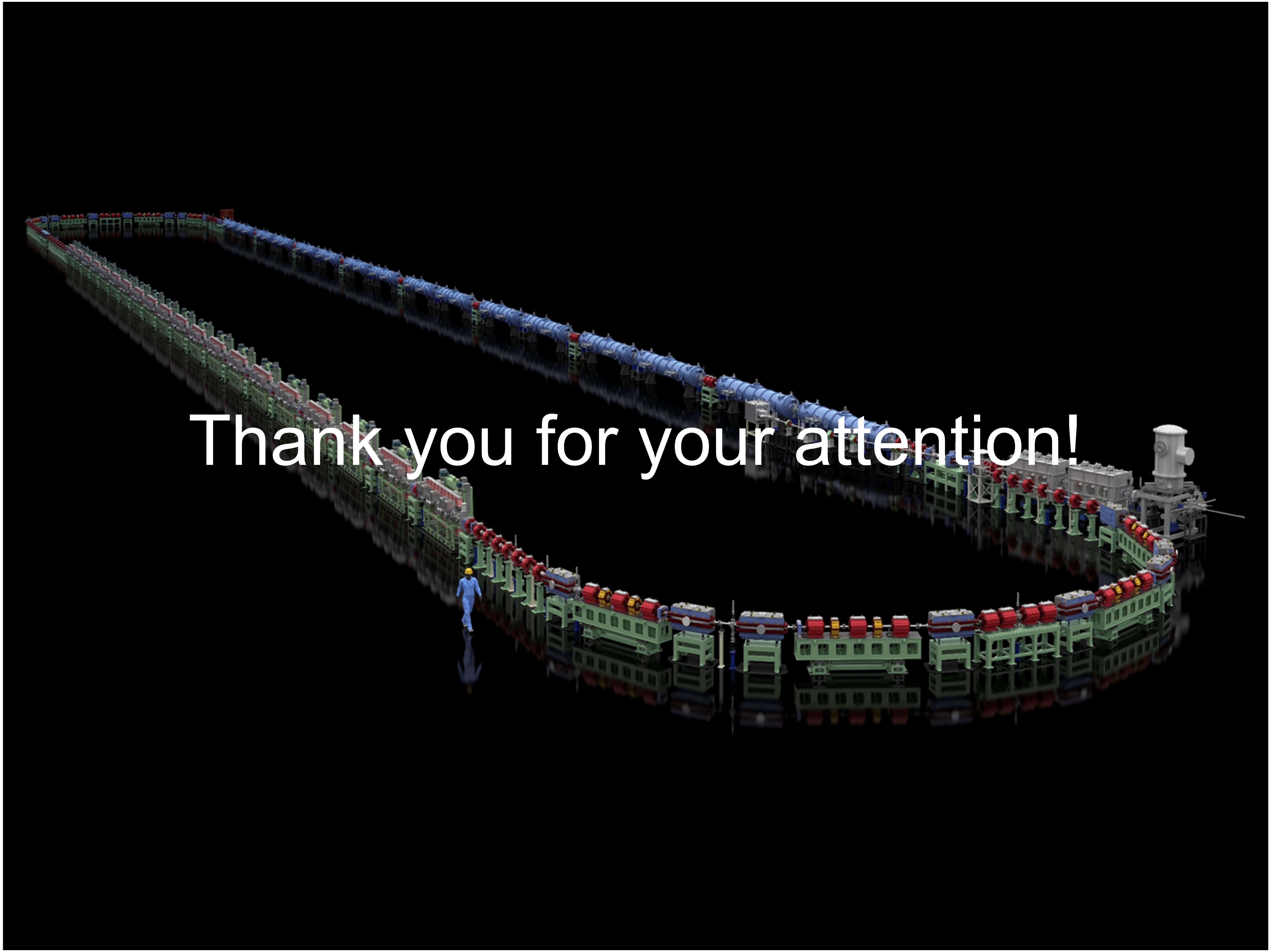






Summary

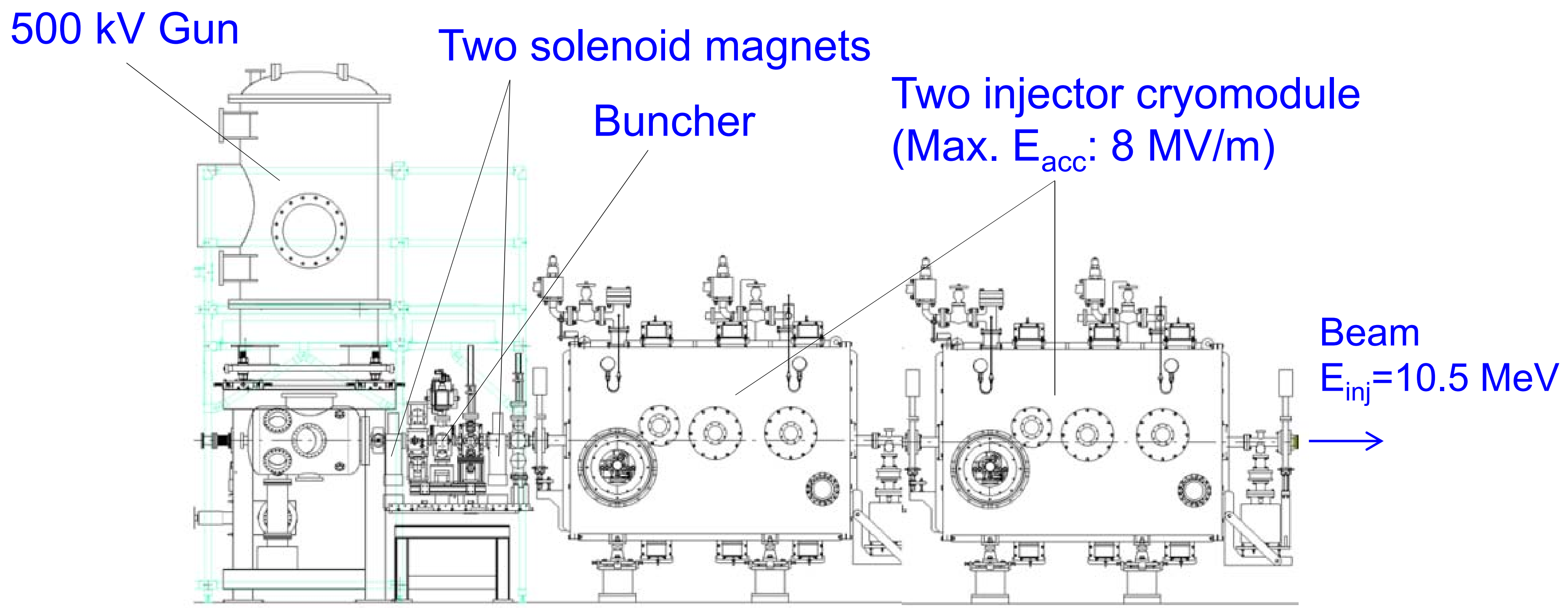
- Compact ERL operation started at 2014. Beam quality is improved since then.
- Based on Compact ERL technology, we have designed EUV light source accelerator based on ERL-FEL.
- For 10kW FEL output of 13.5nm, 800 MeV and 10 mA beam is needed.
- Simulation study is on going. 10kW lasing seems to be possible.
- Based on Compact ERL and STF technology, we have also designed EUV-FEL main linac cryomodule.
- While details are still under discussion, general concept of cyromodule is shown.


Thank you for your attention!

Backup slide

Injector Design

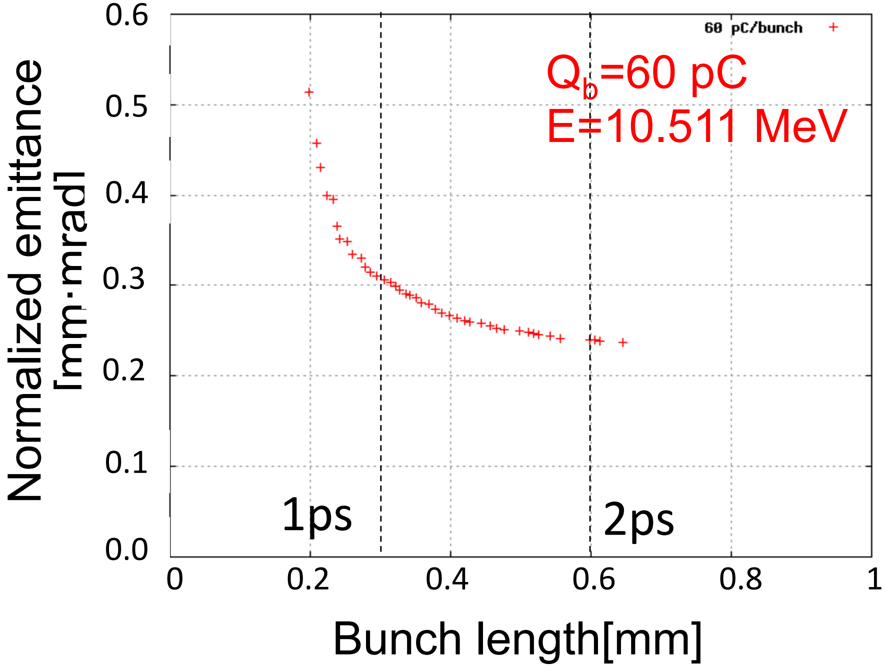
- DC Photocathode gun with the same structure of 2nd gun at cERL
- Two cERL cryomodules with six 2-cell SC cavities for E_{inj}=10.5 MeV
- Two solenoid magnets and one buncher cavity
- New merger (under design)

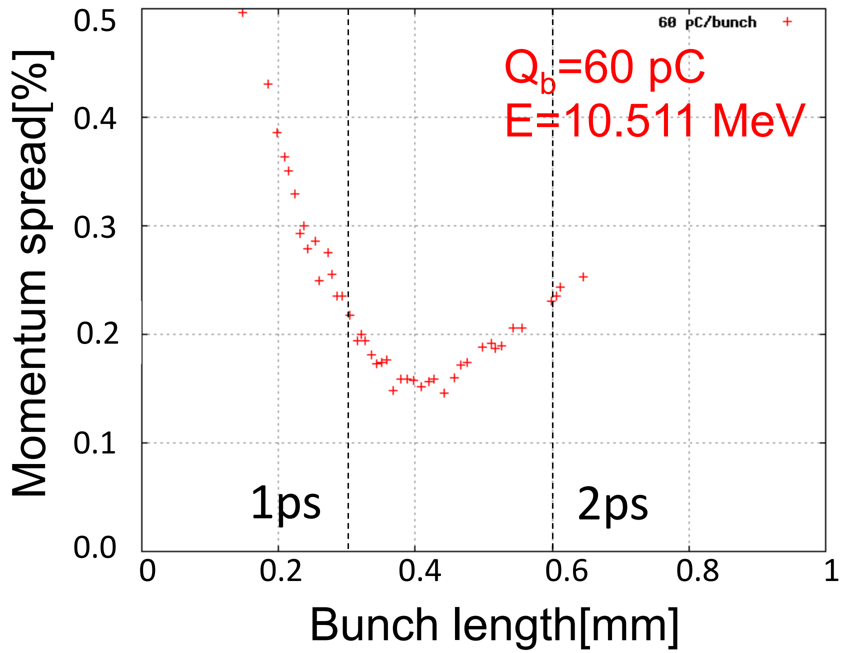


Injector system of EUV source (merger not included)

Injector Parameters

Optimization of injector parameters before merger





Tracking by GPT

60pC/bunch

1 ps : 0.30 mm mrad, 0.25 % → ε_n = 0.60 mm·mrad, σ_p/p = 0.25 % @ merger exit

2 ps : 0.25 mm mrad, 0.25 % → ε_n = 0.55 mm·mrad, σ_p/p = 0.25 % @ merger exit

100pC/bunch

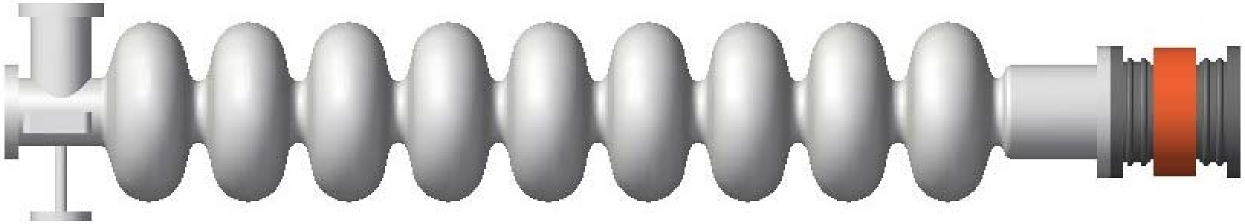
1 ps : 0.57 mm mrad, 0.35 % → ε_n = 0.80 mm·mrad, σ_p/p = 0.35 % @ merger exit

2 ps : 0.35 mm mrad, 0.16 % → ε_n = 0.60 mm·mrad, σ_p/p = 0.16 % @ merger exit

The results are used as initial values for simulations including bunch compression.

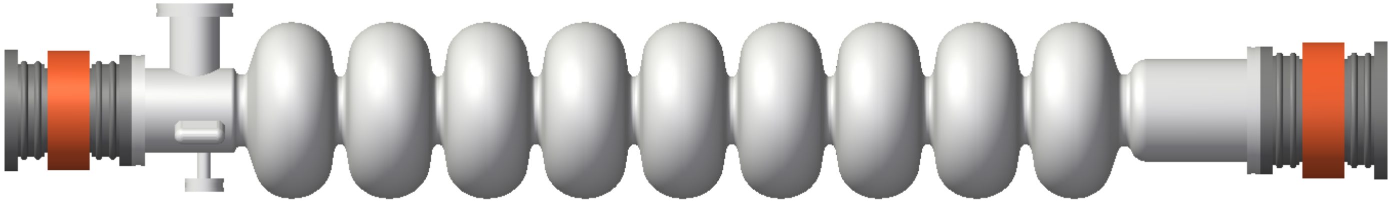
Design of Main Linac Cavity

ERL-EUV cavity (Model 1) – TESLA-type 9-cell cavity + 108ϕ beam pipe



Under design. A large-aperture beam pipe will be also applied to the left side.

cERL cavity (Model 2) – stably operated at ~8.5 MV/m

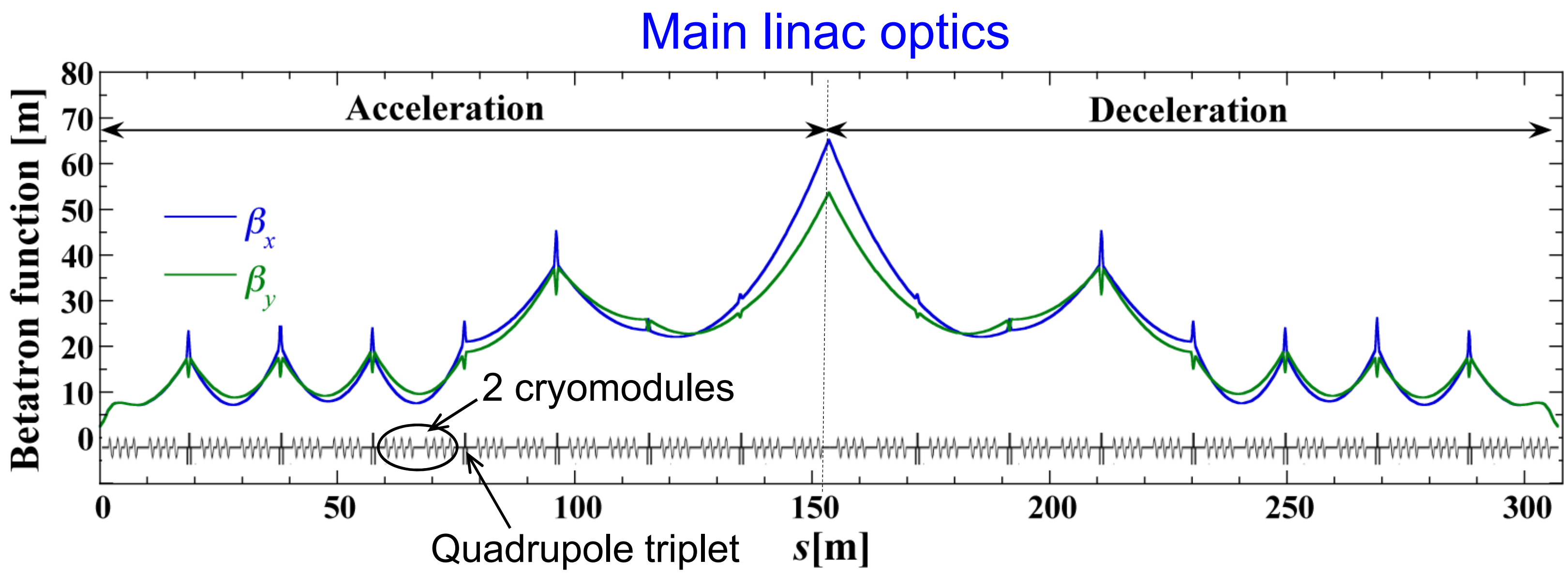


Parameters for acceleration mode

	Model 2	Model 1		Model 2	Model 1
Frequency	1300 MHz	**1300 MHz**	Iris diameter	80 mm	70 mm
R_{sh}/Q	897 Ω	**1007 Ω**	$Q_o \times R_s$	289 Ω	272 Ω
E_p/E_{acc}	3.0	**2.0**	H_p/E_{acc}	42.5 Oe/(MV/m)	42.0 Oe/(MV/m)

Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.

Main Linac Optics



- Main Linac
  - 64 cavities in 16 cryomodules (4 cavities/cryomodule)
  - $E_{acc} \approx 12.5$ MV/m
- Optics
  - Focusing of quadrupole triplet at every two cryomodules
  - Body/edge focusing of cavities
  - Betatron function optimization against BBU → $I_{th,BBU} > 190$ mA
  - Symmetric for acceleration and deceleration

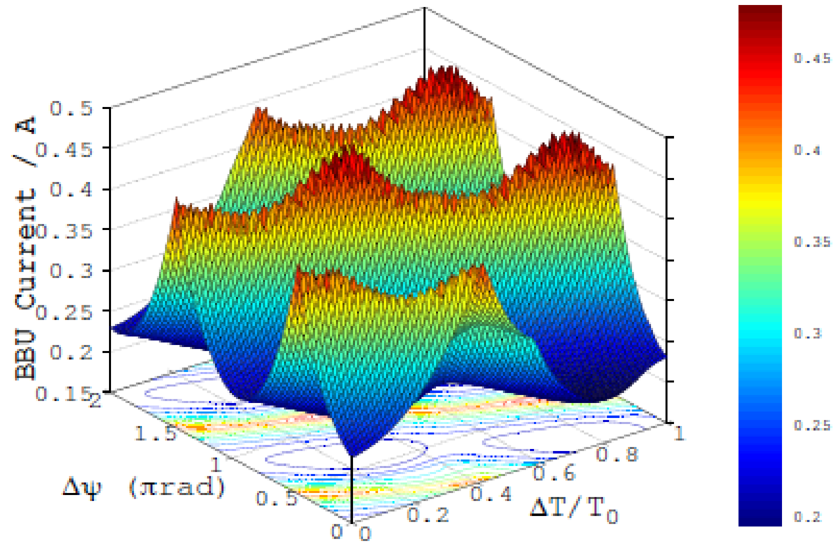
HOM BBU

HOM-BBU threshold current is calculated by Simulation code *bi*.

HOM parameters of Model 1 cavity

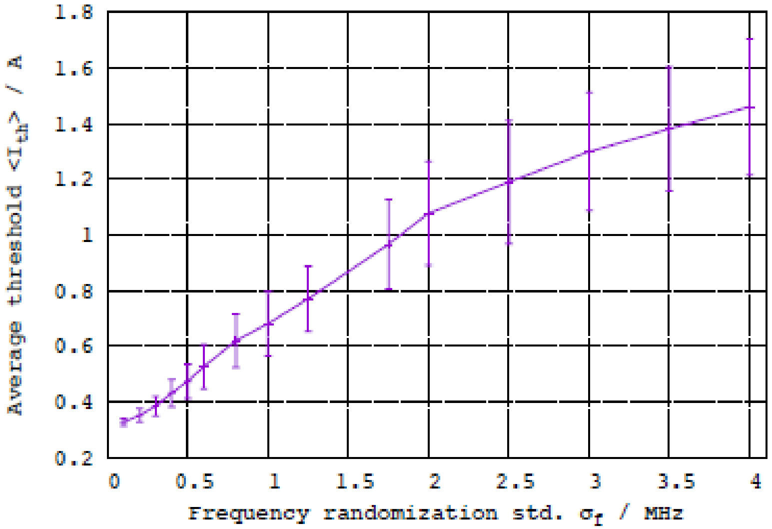
f	Q_e	R/Q	$(R/Q)\,Q_e/f$	$ModeType$
$[GHz]$		$[\Omega/cm^2]$	$[\Omega/cm^2/GHz]$	
1.866	7732	6.43	26659	TM_{110} $6\pi/9$
1.874	11655	8.77	54526	TM_{110} $5\pi/9$
1.879	18360	1.95	19089	TM_{110} $4\pi/9$
2.575	4899	21.32	40557	TE_{121} $\pi/9$
3.082	33608	0.98	10676	TM_{121} $5\pi/9$

Calculation of BBU threshold current



Scan over the betatron phase advance (0-2π) and return loop length (in one period of the base mode). Minimum BBU current is found to be about 195 mA. (478mA maximum).

HOM randomization effects



Considering a Gaussian frequency distribution between linac cavities, the average BBU threshold current grows with the frequency spread σ_f increases, reaching about 1.1A when σ_f =2MHz.

BBU threshold current is well above the expected average current.

HOM Heating

Non-resonant heating

Parasitic loss absorbed at HOM damper

$$P_{loss} = k_{loss} Q_b^2 f_b$$

k_{loss}: Loss factor, Q_b : bunch charge
f_b : bunch frequency

Estimation of loss factor

$$k_{loss} \sim 20 \text{ V/pC @ 1 ps}$$
$$\sim 15 \text{ V/pC @ 2 ps}$$

Examples of parasitic loss power

Bunch length @cavity	9.75mA x 2 60pC 162.5MHz	8mA x 2 100pC 81.25MHz
1 ps	23.4 W	32 W
2 ps	17.6 W	24 W

Max. absorption power of HOM damper :
30 W (first target), 100 W (final goal)

Heating resonant to monopole HOMs

Difference between monopole HOM frequency and harmonics of bunch frequency

momopole f_{HOM} [MHz]	Bunch frequency f_b[MHz]						
	325	260	162.5	135.4	130	100	81.25
2393	207	207	118	44	53	7	45
2427	173	173	152	10	87	27	11
2442	158	158	158	5	102	42	5
2447	153	153	153	10	107	47	10
2452	148	148	148	15	112	52	15
2453	147	147	147	16	113	53	16
2459	141	141	141	22	119	59	22
3848	52	208	52	57	52	48	52
3851	49	211	49	60	49	51	49
3852	48	212	48	61	48	52	48
3853	47	213	47	62	47	53	47

: frequency difference within 10 MHz

Max. absorption power of the HOM damper restricts the bunch charge, length and frequency.
The bunch frequency should be selected so as to avoid the resonant heating.

Comparison STF/cERL/EUV cryomodule

	STF cryomodule	cERL cryomodule	EUV cryomodule
Cavity	TESLA-like 9-cell	HOM damped 9-cell	TESLA type with large beam pipes
Input coupler	Co-axial, double windows, pulse type	Co-axial, double windows, CW type	cERL type with some modification
HOM damper	TESLA type HOM coupler	Ferrite HOM damper	AlN(?) HOM damper with HOM antenna
Frequency tuner	Slide-jack tuner and piezo tuner	Slide-jack tuner and piezo tuner	STF / cERL (same) type
He jacket	230ϕ with magnetic shield inside	300ϕ	STF type
Support structure	Hanging from 2K return pipe	Support by table	STF type with some modification
Gate-valve	Manual gate-valve inside cryomodule	Gate-valve outside cryomodule	STF type with some modification
He liquid surface	He 2phase-pipe	Inside He jacket	STF type with larger chimney